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It is not necessary to carry the analysis farther, since neither theory would be benefitted by the fulfillment or non-fulfillment of these predictions. The question at issue is not met in this manner. It is involved in features lying outside the province of the present paper and is being treated by other authors, as mentioned above.

[1] Castle, W. E., (*a*) "Is the arrangement of the genes in the chromosome linear?" these PROCEEDINGS, 5 1919 (25–32); (*b*) "The linkage system of eight sex-linked characters in Drosophila virilis (data of Metz)," *Ibid.*, 5 (32–36).

[2] Sturtevant, Bridges and Morgan, "The spatial relations of genes," *Ibid.*, **5**, 1919 (168–173).

[3] Castle, W. E., "Are genes linear or non-linear in arrangement?" *Ibid.*, **5**, 1919 (500–506).

[4] Metz, C. W., "The linkage of eight sex-linked characters in Drosophila virilis," *Genetics*, **3**, 1918 (107–134).

[5] See Metz and Bridges, these PROCEEDINGS, **3**, 1917 (673–678). Before the hairy stock was lost some data on the value hairy-magenta were obtained by Weinstein, as noted by Muller (*Amer. Nat.*, **54**, p. 118), but the numbers were hardly large enough to be conclusive.

[6] Assuming, of course, that crossing-over is a consistent process, and that the experiments are conducted under similar conditions.

[7] My data, in the cases under consideration, include only relatively small numbers and give ratios of only approximate accuracy, as indicated in my paper. This fact alone would vitiate predictions of short distances (such as the first two) even if they were otherwise valid.

THE FUNCTIONS OF INTENSITY AND PHASE IN THE BINAURAL LOCATION OF PURE TONES

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The permanence of the value of knowledge concerning the physical aspects of audition gives to contributions in this field a greater importance that is at first apparent. There has been much confusion as to the factors involved in the binaural location of sounds. An analysis of the problem of ascertaining the important factors and their relative values show that the solution will be secured most speedily by the separate control of these factors and by using first pure and then complex tones. This report includes experiments covering the frequency range of 100 to 1200 d.v., the results giving the effects of intensity differences and phase differences at the ears, each factor treated first alone and then in combination.

Intensity.—Rayleigh (*Phil. Mag.*, **13**, 1907 (214)) was the first to point out that for frequencies of 128 and 256 d.v., the difference in intensity at the ears could not account for the ability to locate the source of sound. Although there have been many experimental contributions in the localization of sound, the only observers to make quantitative measurements of the effect of intensity were Hovda and the writer (*Psych. Rev.*, **25**, 1918, 3 (242)). They found that, for a frequency of 256 d.v., if the difference of phase at the ears was kept zero but the ratio of intensities varied, there appeared a moving phantom source having a position in front, for an intensity ratio of unity, and rotating horizontally about the observer, its angular displacement from the median plane being proportional to the logarithm of the ratio of the intensities at the two ears, the constant of proportionality varying for the individual and for the frequency. This logarithmic law has now been further tested for frequencies of 512 and 1024 d.v., and has been found to be correct for displacements from the median plane, less than 90°, excepting that for the 1024 d.v. some individuals do not get a moving phantom source of the fused sound. It would thus appear that intensity might have an important influence in localization. But such a conclusion must involve a quantitative test. Assume a source of sound at a distance of five meters from the observer and carried in a circle about him. It is possible, by means of theory (Stewart, *Physic. Rev.*, **33,** 1911 (467)), to compute the ratio of intensities at the ears produced by such a source at different angular displacements from the median plane. But one can, by means of the experiments already mentioned, ascertain what apparent angular displacements would be produced by the computed intensity ratios. Do these computed displacements agree with the actual? If they do, obviously intensity is an important factor in the actual case. But they do not agree quantitatively. For example, if the displacement of the source was 60°, the computed displacements for one observer were as follows: for 256 d.v., 6.1°, for 512 d.v., 13.8°, and for 1024 d.v., 11.2°. For a second observer, and the last two frequencies, the computed angles were 9.1° and 9.1°. A careful examination of all angular displacements up to 90° showed a similar lack of correspondence. Obviously the intensity effect cannot account for the ability to locate sounds. It does not appear to be even an important factor.

Experiments showed that for some people (two out of four observers) the intensity effect disappeared entirely in a certain frequency region. With each of four observers the intensity effect in a relatively large frequency region involved not only a moving phantom source of sound, but also an additional one stationary and in front, or in a position corresponding to the difference of phase.

The logarithmic law of Stewart and Hovda appears not to be merely an extension of Weber's Law, as at first announced.

Phase.—That phase difference affects the localization of a sound source, has been known for a number of years. (Review of literature; Stewart *Physic. Rev.*, **9,** June, 1917 (502).) Hartley (*Physic. Rev.*, **13,** 1919 (373)), has produced evidence in favor of the conclusion that the phase difference of a pure tone at the ears is the controlling factor. The present report presents a considerable addition to this evidence and that of a quantitative character. In the experiments, frequencies from approximately

100 to 1200 d.v. were used. Purity of tone was approximated in a special apparatus, but the results were checked by tones from tuning forks and hence the conclusions are reliable. It was found that, if the phase differences at the two ears were varied, intensities remaining equal and constant, the angular displacement of the phantom sound from the median plane was proportional to the phase difference at the ears. Inasmuch as the theoretical phase differences at the ears were known (Stewart, *Physic. Rev.*, **4,** 1914 (252) and Hartley, *Ibid.*, **13,** 1919 (373)), it became possible to ascertain whether or not the relationship between phase difference and angular displacement was quantitatively the same as in the experiments just mentioned. When the comparison was made, it was found that there was a reasonably close quantitative agreement, i.e., the difference over practically all of the range was, on the average, less than 10%. In fact, the correspondence between results in the theoretical case and in the experimental one was so striking as to leave no doubt as to the fact that *phase* must be the *most important* factor in localization in the region 100 to 1200 d.v.

As can be readily understood, the higher the frequency the less that displacement from the median plane for which the phase difference is 180°. For 1024 d.v., this displacement is 41°. But this is not the maximum angle for which a source can be located by phase. This was shown by the existence of multiple phantoms or images. Thus the conclusion already stated seems worthy of full confidence as applicable for a displacement of less than 90° in front. This does not close the case with pure tones for there is yet to be ascertained what additional factors are of moment in locating a source not in the horizontal plane and not in front of the observer.

That it is impossible to explain the difference of phase effect in terms of intensities, either by bone conduction or otherwise, is proved by the fact that the difference of phase effect was clearly present at 1024 d.v., with two observers who could not at this frequency get the intensity effect at all, i.e., the moving phantom source occasioned by altering intensity ratios was not present. The necessary conclusion is that the ears do perceive phase differences.

The difference of phase effect ceased with increasing frequency at a frequency of 1200 to 1500 d.v. This was tried with four observers. When the effect ceased the phantom sound remained in the median plane with changing phase.

Intensity and phase combined.—Experiments in which phase and intensity differences were simultaneously applied showed that the actual relative importance of either of the two does not change in the combination. Thus the effect of an intensity difference at the ears merely made a relatively slight change in the angular displacement of the phantom source. Consequently our conclusions formed by phase difference alteration, only, are approximately correct for the actual case of location wherein both phase and intensity are altered.

The work thus far clearly shows that with frequencies 100 to 1200 d.v phase is the *chief* factor in localization with pure tones. For the lower frequencies the intensity effect is practically nil, and at all frequencies within the range considered the effect must be small. These conclusions are quite contrary to the view commonly held and appearing in psychological literature and texts. But they are worthy of confidence because based on *quantitative* results, and not on personal judgment. There remains a great amount of experimental work covering an extension of the frequencies and the employment of complex tones. Strictly speaking the localization herein mentioned applies only to 90° either side of the median plane and in front. The removal of this limitation will probably prove relatively simple after the experiments are completed. The above report while covering a limited range, nevertheless does make a definite advance in our understanding of the relative importance of the factors, phase and intensity, in binaural localization, and furnishes a basis upon which the future experiments may depend.

THE MEASUREMENT OF SMALL TIME INTERVALS AND SOME APPLICATIONS, PRINCIPALLY BALLISTIC[1]

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Precision in time calibration is of importance in many classes of research. Several types of apparatus have been developed for this purpose. Some of these, such as the Helmholtz pendulum, permit extremely accurate reproduction of a stated interval but less exact absolute determination. A method proposed and extensively used by A. G. Webster has given satisfactory, absolute determinations of intervals as small as a millionth of a second.[2] The recording apparatus is electrical and the calibration is accomplished by a careful measurement of the height of fall of a projectile.

The Le Boulengé and the Aberdeen chronographs are in general use, the former having a falling projectile and the latter a rotating drum. With any apparatus involving a rotating drum, it is necessary to maintain the speed of the motor driving it within certain limits and to secure a dependable calibration, usually placed on the record as it is being made. Various instruments have been devised to accomplish this purpose.[3] A tuning fork producing a photographic or mechanically inscribed record of a sinuous form is perhaps the commonest example.

Means for applying discontinuously a record of a fork or other vibrator